The Science of Paddling

First Edition

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Preview Chapter

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Mark McAndrew of Paddlesport Training Systems (www.paddlesporttraining.com) for the paddling ergometer adapter photograph, Fig. 18.6.

Introduction

One Summer evening in 2008, our Tuesday training group was paddling back to the boat ramp on the Contoocook River after a long session on the water. This night saw us moving together in a pack at a moderate pace, interspersed with sprints at turns in the river. We were idly chatting during a lull in the action when my friend Tom pulled alongside, turned, and asked me, "Why can't two people paddle a tandem canoe twice as fast as a solo paddled by one?"

I had no idea. But I knew that I should, and that bugged me.

As an engineer, I find paddling not only fun but technically fascinating. Spending hours at a time on an indoor paddling trainer in Winter and on the water when it's not frozen here in New England has given me time to ponder my sport. Tom's query resonated because I'm curious about why things work. Despite my education and training, I'd always glossed over the specifics for paddling until he posed that question. Canoes move when paddled; isn't that enough? Obviously, "science is happening," but how? I'd offered the occasional nod to Isaac Newton's 3rd Law of action-reaction, which requires that the stern-directed paddle force results in the hull moving forward. Or I cited Archimedes' "Eureka!" moment, revealing why particular combinations of weight and displaced hull volume predict some things will float while others sink. Beyond that, my understanding of the *why* was shallow. I knew more about what to do than why things happen.

From experience, I knew that an empty canoe (usually) passes unscathed through a series of rapids. A kayak slows down in shoals yet naturally speeds up as it passes into deeper water. Plus so many other phenomena that I had experienced, but mainly as a passive observer. The overarching questions became, *why do paddled hulls do what they do*? And is paddling fundamentally different than other sports in how it engages the body? The hull and the water know what to do – that's their nature. To understand what they know, to get at the *why*, we must learn their language: the language of science. My investigations cast a new light on years of paddling. What I learned was enriching and sometimes counter intuitive; that's where the fun is. And that's why I want to share what I've learned with you.

The Science of Paddling addresses the why question of paddled hulls. The concepts presented here apply to canoes, kayaks, surfskis, outriggers, and SUPs. All these craft have four things in common: a hull, at least one paddle, one or more paddlers, and water. I've limited myself to topics that are broadly applicable, rather targeting a specific hull model or brand of paddle. Consequently, what you'll learn applies to you and your craft.

Along the way you'll find ways to make your paddling more efficient, allowing you to travel further, faster, and with less effort. Competitive paddlers will see that physics can guide their training to be more paddling-specific. And finally, I hope that like me you discover the simple joy of understanding our favorite sport, and gaining a new appreciation for the wonder of gliding across the water.

Organization and Audience

In developing this book, I found that topics follow a progression, naturally divided into two portions. In the first part, Chapters 1 through 7, we construct the foundation for later applications, with topics building one upon the other. We address why a hull is buoyant, why it moves, what opposes its motion, and why a paddle propels it. Core concepts from classical physics are introduced and applied in context: Newton's Laws of Motion, energy conservation, and mass conservation. You'll see that these principles are merely precise statements that represent our everyday experiences of the world around us.

The foundation laid in the first seven chapters lets us then explore several applications. Topics include trim's effect on handling, how to measure your hull's drag coefficient, why we always lose time on an out-and-back route in current, how physics can ensure all paddlers are treated equally in race scoring, and how endurance and strength training can be optimized for our sport. Woven throughout are reflections on how engineers approach problem solving.

Each chapter is organized as follows:

- THE TOPIC: problem statement, modeling and analysis, and conclusions. Primarily text exposition, with analysis limited to algebra and geometry at most.
- TAKE-AWAYS: bullet points that summarize the main points from the chapter. Here, I offer pub quiz-ready talking points for the main questions addressed.
- EXTRA CREDIT: detailed modeling or analysis is presented for the interested reader – the general reader loses nothing by skipping over these parts or returning to them later.
- FURTHER READING: references are included for those who wish to dive deeper into the chapter's subject matter.

This structure lets readers explore the material at whatever depth they wish. You needn't have a degree in science, engineering, or mathematics to learn about the why of paddled hulls. Just an open and curious mind.

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CHAPTER 0

Newton's Laws of Motion

Introduction

Quick: Name Newton's Laws of Motion. Are you able to recite all three? (Do you know there are three?) Are you comfortable describing at least one practical example of each?

These questions aren't intended to put you on the spot. But most of *The Science of Paddling* relies upon the Laws of Motion to explore the why of paddlesport. The good news is that the Laws are empirical. They were developed based on observations of the real world, describing things we see around us all day and every day. They are straightforward and have a certain elegant simplicity, and can be stated and understood without resorting to mathematics. While their implications and applications are vast, we'll confine ourselves to paddling.

If you answered in the affirmative to the questions above, feel free to skip this overview and move right into the heart of the book. If you need to get more familiar with the Laws, this brief review should get you up to speed. Even if you're a classical physics gunslinger, you might enjoy the historical context and original presentation of the 2nd Law.

The Laws of Motion

In 1665 Isaac Newton completed his undergraduate studies at Trinity College, Cambridge. The Great Plague had descended upon London, so Newton retired to his family's farm at Woolsthorpe Manor, Grantham. Over the ensuing year – what has been referred to as the "year of wonders" – Newton formulated new theories of physics and mathematics that underlie much of modern science and engineering. He showed that the movements of planets, moons, and other celestial objects, and the motion of things here on Earth, could be described in a single, unified framework. Newton did this using only algebra and geometry. Along the way, he developed differential calculus.

In 1687 Newton published his discoveries in the text *Philosophiæ Naturalis Principia Mathematica* ("Mathematical Theory of Natural Philosophy," commonly referred to as the *Principia*). The most well-known elements of this are his three Laws of Motion. We refer to them as laws because they're axiomatic. Newton saw them as self-evident truths that describe phenomena we routinely observe in the physical environment.

Everything that happens when we're in a hull can be described by Newton's laws of motion: why we float in the first place, stability, the various forces acting on the hull and paddle(s), why a hull moves when we paddle, the effect of trim, etc. So, as you read *The Science of Paddling*, know that you're both going old school (i.e., 17th century) and are in very, very good company.

This brief preface will review the three Laws of Motion and summarize how they relate to our favorite sport.

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The 1st Law states:[1]

> Every body perseveres in its state of being at rest or of moving uniformly straight forward, except insofar as it is compelled to change its state by forces impressed.

First, this means that an object ("body") like a canoe, kayak, or SUP will remain stationary unless you lift it up from the storage rack, or apply a paddling force when it is motionless atop quiet water. Stationary is one example of a hull's "state."

The other state is a hull moving forward at a constant (uniform) speed along a straight course.[2] From experience, we know that if we apply a forward paddling stroke, the hull will no longer move at a constant speed but will instead speed up. The force of the paddling stroke has "compelled" the hull to change its state from one speed to another. If we apply a corrective stroke, such as a draw or pry, we are compelling the hull to change its state from moving straight to turning. We also know from experience that a hull slows down when we are no longer "compelling" it. This is because drag forces – friction, form, and wave – are "impressed" upon the hull, constantly changing its state from one speed to another. Finally, changes in trim can induce asymmetric forces fore-and-aft that compel a hull to turn and then attain a new heading when acted upon by the dynamic pressure (in effect, a force) of current.

1 Newton's *Principla* was written in Latin, the 17th century's *lingua franca*. The translations of the laws of motion used here are from Bernard Cohen and Anne Whitman, *The Principia: Mathematical Principles of Natural Philosophy*, University of California Press, Oakland, California (1999).

2 A stationary hull has zero speed in any direction. This is a trivial special case of "moving uniformly." Newton may have anticipated folks would quibble if he didn't separately name this as the rest state.

As you read through these examples embodying the 1st Law, visualize each scenario: where the various forces act (are impressed) and how the hull responds (changes its state). Most likely, you have compelled a hull to change its state by forces impressed in many ways. You may not have referred to it in quite those terms.

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The 2nd Law states:

> A change in motion is proportional to the motive force impressed and takes place along the straight line in which that force is impressed.

Compare the 1st and 2nd Laws. In the 1st, Newton cites "force," while in the 2nd, he cites "motive force." This means we're talking about two different categories of force. Here motive force means impulsive force. Note also how the body in the 1st Law has a state, while in the 2nd, it has "motion." By motion, Newton meant *momentum*, which is the product of an object's mass and velocity. Consequently, a change in an applied impulse force, such as that delivered over a paddle stroke, changes the momentum of the hull/paddler system.

In Chapter 4, we'll see that momentum has a direction since it is the product of mass (a scalar, which is directionless) and velocity (which has a direction and therefore is a vector). For example, suppose you paddle out of a quiet shoreline eddy into a river's current, aiming straight for the far shore. The force exerted by the incoming current acts perpendicular to your intended direction of travel. This will move you downstream. The degree that your direction of travel is deflected depends on the dynamic force of the current vs. the force generated by your paddling strokes. We'll cover this in Chapters 6 and 9.

Since the change in impulsive force is proportional to the change in momentum, if you double the impulsive force, the resulting change in momentum also doubles; tripling leads to tripling, etc. The more impulse you generate by paddling strokes, the faster you go. We'll explore this in Chapter 7.

As we'll see in Chapter 2, after adopting a hull-centric reference frame, the wake behind a moving hull reflects a change in the incoming water's momentum. This change in momentum exerts itself as the *form drag* force on the hull.

Those of you who took high school physics, or studied engineering or science in college, likely learned that the 2nd Law is "force equals mass times acceleration." Why are these two statements apparently different? We'll cover that in the Extra Credit section.

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The 3rd Law states:

> To any action there is always an opposite and equal reaction; in other words, the actions of two bodies upon each other are always equal and always opposite in direction.

Here, "action" refers to force. Newton wrote the 3rd Law to encompass orbiting celestial bodies, billiard balls bouncing off each other, and objects in static equilibrium.

Newton's argument that the Earth and Moon are mutually attracted by gravitation forces was highly contentious when he proposed it. Critics claimed he had introduced invisible "occult forces" to make his mechanics work. When pressed as to what gravity was (as opposed to what it *did*), he famously wrote, "*Hypotheses non fingo*," or "I frame no hypothesis." His was an applied, empirical science and not merely philosophy. It would take a few centuries before Albert Einstein showed that objects having mass warp the fabric of space and time, thus creating the effect we call gravity. In the meantime, Newton's laws worked, and they still do.

We experience the 3rd Law when we place one of our hulls in the water. The hull floats. This is because the hull displaces a volume of water, leading to a buoyancy force that precisely equals the hull's weight. The buoyancy force acts upward, while the weight of the hull acts downward in the direction of gravity's pull. When we climb aboard our hull, it sinks lower, displacing a further volume of water whose weight equals our own. If we remain afloat, these opposing forces – buoyancy and weight – balance each other. Our weight is the "action," while the buoyant force is the "reaction." We'll dig into this more in Chapter 5 when investigating a hull's stability in roll.

You're also experiencing the 3rd Law while reading this. I'll assume you're sitting on a chair or couch. Your weight exerts a downward force due to gravity: an "action." The chair is exerting a reaction force in response to this action. These two forces precisely balance each other. Otherwise, your weight will cause the chair to collapse. At that point, you've entered the regime described by the 1st Law, moving downward until another force stops you. Looking around the room you are sitting in now, you may notice many objects sitting atop shelves, tables, the floor, etc. Each of these objects exerts a downward force equal to its weight. The shelves, tables, and floor beneath these produce reaction forces to keep things from falling through the floor. Newton's 3rd Law is all around us all day long.

Extra Credit

When Newton wrote the *Principia*, calculus hadn't been invented; he was inventing calculus as he went (as was Gottfried Leibniz in parallel). Newton's work was couched in algebra and geometry. His original statement of the 2nd Law doesn't use the words "rate of change" or "rate of change with respect to time." This is how we now describe acceleration in terms of velocity. These are concepts we take for granted; in the 17th century, they were hotly debated.[3] The rate of change is now commonly used because we have differential calculus.

Here's how you can derive the familiar relation between force, mass, and acceleration from Newton's original wording of the 2nd Law. First, in Chapter 7, you'll learn that an impulsive force – the product of force and the time interval over which it is applied – is related to a change in momentum via

3 See Amir Alexander, *Infinitesimal: How a Dangerous Mathematical Theory Shaped the World*, Scientific American / Farrar, Strauss and Girous, New York (2014).

$$F_p \Delta t = m \Delta v \,, \tag{0.1}$$

where F_p is the propulsive force, which for paddlers is the paddle reaction force in the direction of travel. For paddlers, the combined mass of hull, paddler(s), and gear is *m*; *t* is time, and *v* is velocity. Δt signifies an interval of time, while Δv indicates a change in velocity in response to the impulsive force. If we divide both sides of the equation above by Δt,

$$F_p = m \frac{\Delta v}{\Delta t} \ . \tag{0.2}$$

We'll now introduce a highly controversial concept from Newton's time: infinitesimals. Suppose we let the change in time Δt become infinitesimally small. In that case, the fraction on the right-hand side of this equation represents the instantaneous change in velocity over that infinitesimal period. In the limit as Δt approaches zero, this fraction represents the hull/paddler system's instantaneous acceleration *a*. So, in that limit,

$$F_p = ma \ . \tag{0.3}$$

This is the form of the 2^{nd} Law we likely learned in school. Congratulations: you've just invented differential calculus! Now let's move on to paddling.

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